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VOLCANIC PHYSIOGRAPHY OF THE WESTERN PLAINS OF VICTORIA

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Abstract

94 named points of volcanic eruption occur on the W. plains of Victoria, associated with extensive flows of olivine basalt. The volcanoes take the form of basalt cones, scoria cones, maars and complex types. Vulcanicity probably extended from earliest Pleistocene times to the Recent, with changes in location and type of vulcanicity. There are few lineaments in the pattern of eruption, and since many flows can be related to particular vents it is believed that central eruption was prevalent. Most of the hills are small and although, in many cases, there were successive eruptions from one point, these were probably close together in time and genetically related so that the volcanoes are essentially monogenetic. The explosion index is low, and this combination of features suggests that the Newer Volcanics of Victoria constitute a distinct geomorphic/petrographic province. Physiographic features of the flows, such as tumuli, stony rises, and lava blisters, are frequently well preserved, but in older flows extensive weathering and soil formation has occurred. Dating methods applied to the vulcanicity are reviewed; although comparatively little progress has been made so far, there is ample material available for working out a detailed geomorphic history.

Introduction

The Newer Volcanics of Victoria, which are of perhaps Pliocene to Recent age, occupy much of the SW. of the State both in the W. plains and the W. highlands. In this paper we shall restrict ourselves to the plains, as shown in Hills (1940). Areas to the N. have been described by Coulson (1954) and Yates (1954) among others, and, since these papers mention over 150 points of eruption, there is no room for repetition here. The volcanics of Central Victoria have been described by Edwards (1938), Hanks (1955), and others, and there are many papers dealing with particular areas or topics which we shall refer to later.

In this paper we shall describe in some detail the volcanic physiography of the W. plains, including the volcanic hills which dot the plains, and also discuss some generalities which concern the Newer Volcanics as a whole.

The W. plains were in existence before volcanic activity started, and igneous rocks only veneer a pre-existing surface. Recent work is showing that considerable areas of the plain, in fact, are not underlain by basalt, and the total extent of the lava sheets may be much less than was formerly supposed. Early writers on the area often followed Gregory (1904) in believing that much of the volcanic activity took place in a large lake, a view based on the bedding of pyroclastics (supposedly sub-aqueous) and the general flatness of the area. Hall (1907) disposed of this idea and showed that the tuffs were subaerial deposits, and we now believe that most volcanics were erupted on a recently uplifted plain, although lakes existed in parts for considerable periods, and there would have been a high water table. Currey (1964) has given a description of the former extent of L. Corangamite, and a good deal of volcanic activity post-dates this lake.

The Newer Volcanic Province is remarkable in having a large number of points of eruption, none of which grew to any great size. Almost all the volcanoes are less

than 500 ft above their base and the majority are less than 300 ft. In the Daylesford area, Coulson recorded 123 points of eruption in an area of 600 square miles. In the W. plains we have attempted to record all named volcanoes which number over 90. Some of these are multiple eruptions and there are many other small points of eruption which are not named, but some arbitrary limit had to be set in the compilation.

These many small hills mark points of eruption which poured out large quantities of lava, forming a carapace over much of the plains and giving rise to distinctive landforms; the hills, although very eye-catching, only represent a small portion of the lava erupted.

The relative youth of most of the volcanoes is indicated by the small amount of erosion that they have suffered. Many of them are remarkably well preserved and have just the shapes they had when newly formed. The lack of erosion means that there is a lack of exposure of the interior parts of volcanoes, and opinions must be based on surface exposures and occasionally on exposures in quarries and road cuttings, or on bore records. However, from the shape of the hill and such exposures as there are, it is usually possible to classify the volcanoes.

Types of Volcanoes

Basalt Cones

These are usually low-angle hills, made up of a number of lava flows with no apparent scoria. Mt Atkinson and Mt Cotteril are examples near Melbourne, and on the latter Condon (1951) has mapped individual flows. Other examples are Mt Widderin, Mt Vite Vite, and Mt Rebecca. All of these are weathered and have little or no sign of a crater. Mt Hamilton is a perfect lava cone, with a large crater ¼ mile wide and 100 ft deep. The crater has steep inner walls which are unbreached, but the outer slopes are only about 4°, merging into the plain around.

Basalt without scoria seems to have been erupted at Lawaluk, but this is not a simple cone but a steep-edged, flat-topped disc of lava. Mondilibi is probably of the same type, and the lava sheet within the ring barrier at Mt Porndon (Skeats and James 1937) is possibly a similar, though larger, feature. Warrion Hill is a basalt complex forming an elevated plateau with a diameter of over a mile, and having steep sides with many lava outcrops.

Basalt hills are not as common as scoria hills and, in general, appear to be older.

Scoria Cones

The ideal scoria cone is a single cone with steep sides and a crater at the top. Mt Elephant and Mt Noorat are two very good examples. The even height of the crater rim often causes the hills to look flat-topped from a distance, like a truncated cone. Many mountains are multiple cones, where several eruptions have taken place from a number of vents in close proximity, so that the scoria cones overlap to form irregular hills, and in some cases it is not easy to find the actual points of eruption. Robertson's Hill, Mt Shadwell, Meningorot, and Mt Wiridgil are of this type. The ejectamenta shows a wide range of variation from coarse bombs and blocks to fine ash. The coarser the fragments the steeper is the hill that results. Sometimes the scoria is welded together, especially close to crater rims. Mt Noorat and Mt Napier show very steep crater edges made of welded scoria. Bombs are common on some volcanoes, such as Mt Porndon, Mt Noorat, and the Anakies. These may contain cores of basalt, olivine (peridotite), or the local country rock. Country rock frag-

ments may also be thrown out along with the general scoria, but without the wrapping of lava to make a typical bomb. At the Anakies, granite is thrown up (one block of several tons is reported), at Mt Rouse quartz fragments, at Elingamite and Wangoom limestone fragments, and at Cape Bridgewater fragments of shale and hornfels. Bombs have been described in more detail by Baker (1964).

Around the rims of scoria cones may be found walls or heaps of lava which congealed on reaching the surface, probably being more viscous than normal. Sometimes they have the appearance of dykes but it is hard to see them as true dykes connected to a magma chamber as they have failed to produce flows. They may be due to the squeezing out of residual liquid from the scoria of the cone along lines of weakness during compaction or settling, possibly accompanied by faulting. The rim of the crater is one line of weakness where such squeeze-ups are found, as at Mt Myrtoon, Mt Warrnambool, and Mt Rouse.

Contrasting with these rim squeeze-ups are the linear squeeze-ups found at Mt Anakie, Mt Rebecca, and Mt Warrnambool. These are long ridges on the flanks of the volcano, and are probably of similar origin to the first type. Others may be radial, while at Mt Misery an unusual curved squeeze-up runs through the centres of three circular outcrops of basalt, which appear to mark the positions of former craters. Similar curved outcrops are found at The Cap.

The highest scoria cone on the W. plains is Mt Elephant which rises some 780 ft above its base. Other cones are about 500 ft high, but most are 300 ft or less (see Table 2).

Maars or Tuff Rings

These are low rings or ramparts of pyroclastic material surrounding wide but comparatively shallow craters. There is some confusion about the terminology. Some authorities say real maars are formed of only country rock, thrown out by a volcanic explosion which did not erupt any volcanic rock, and that if the ejectamenta contains much pyroclastic material then a 'tuff ring' is formed. Rittmann (1962), however, restricts 'tuff ring' to those landforms of indurated pyroclastics, and 'maar' to the crater lakes within them. We will use the term 'maar' for both the outer ring (consisting of pyroclastics or country rock) and the lake. Most of the landforms, in fact, do have lakes in them, and the geographical place names often refer to the lake rather than to the ring which encloses it.

There is a considerable variation in the amount of country rock contained in the ejectamenta. Wangoom Hill consists almost entirely of limestone fragments in the S. quarry at least, but there are also pieces of dense black basalt. Elingamite is mainly pyroclastic but has a few fragments of limestone, as does Mt Ewan, while Purrumbete is almost entirely volcanic ash.

The typical form is a circular ring of pyroclastics, steep on the inside and very gentle on the outside (3-4°), merging into the surrounding plain. The craters are ½ to 1 mile in diameter, and the walls go up to about 50 ft typically, although in exceptional cases, such as Bullenmerri, they may be higher. There is often an asymmetrical distribution of ash, with high walls on the E. side, and low walls, or no walls at all, on the W. This distribution is not always present, and Munderong is lowest to the N.

Many maars contain lakes, such as Purrumbete, Gnotuk, Elingamite, and Bullenmerri. Some, such as Munderong and Cobrico, are swampy and others, such as Terang and Wangoom, are dry. Those with lakes may suffer 'coastal erosion', as can be seen on the E. downwind side of L. Elingamite where the rampart is cliffed

and a small beach has formed. The water levels in the maars have not remained constant, and old beach levels may be found, as at Keilambete, Gnotuk, and Bullenmerri.

The pyroclastic material shows distinct bedding, which dips outward from the crater at the same low angle as the ground surface. The ash beds originate with periodic ejections during a single eruption, the material becoming sorted during its descent. Purrumbete also shows cross bedding in the outward dipping ash, indicating that wind action has a part in the sorting and deposition too.

Purrumbete is also unusual in having inward dipping bedding in the ash on the inside of the crater rim. This is steeper than the bedding on the outside, and shows much scour and fill (possibly achieved in the dry state), and landsliding. Inward dipping tuffs have been found also at Mt Leura. It is much more common for the outward dipping ash beds to be truncated at the inner edge, as at Tower Hill. This is most probably due to the crater walls collapsing into the empty vent after the eruption, but whether this is on a scale sufficient to regard the maars as calderas is open to question.

The flat floors of the drained and swampy maars, such as Terang, Wangoom, and Cobrico, indicate considerable infilling of the original crater, though what the filling consists of, and when it happened, is not yet known. Other maars, however, have deep lakes, such as Gnotuk (103 ft), Bullenmerri (263 ft) and Purrumbete (150 ft) (see Fig. 1).

The separation of maars from scoria cones at times can be difficult, and a continuous series can be postulated as from Elingamite (perfectly circular and shallow) to Purrumbete (rough circle) to Gnotuk and Bullenmerri (more irregular in outline), the latter, according to Hills, being three coalesced craters. It is then only a short step to The Basins (a multiple scoria cone with two wide craters containing round or oval lakes) and then to Red Rock (which has 7 craters and 5 broad lakes, and rises to 300 ft above lake level). If Red Rock were a little higher above the water table it might resemble a multiple scoria cone such as Mt Shadwell, and there would be a complete transition from maar to scoria cone. Despite the presence of transitional types, the separation of maars from scoria cones seems worth while, and our main criterion has been the presence of thin-bedded ash layers in the low angle outer ring.

With the exception of a few doubtful cases, the maars are concentrated in the Camperdown area, on bedrock of Tertiary limestone, and on a flat plain where groundwater is near the surface, perhaps causing the explosive eruption.

Calderas

According to Howell Williams (1941), calderas are large depressions, usually over a mile wide, and formed by volcanic subsidence. It is generally agreed that Tower Hill is a caldera, but it should be realized that it is the minimum size for a caldera, and its outer edge is similar to that of the maars. Its shape is roughly circular and the 'caldera' lake at Tower Hill is similar to the lakes of the maars. Within it is a multiple scoria cone, so it has been described as a nested caldera or nested crater. The outer wall is highest on the E., as in most of the maars, and the ash is asymmetrically distributed over the surrounding countryside, being mainly to the NE. Gill ascribes this to a south-westerly wind at the time of eruption.

Gill has also suggested that other calderas exist in the W. District, e.g. Ecklin, Mt Warrnambool, Mt Leura, and Wangoom. We regard these as tuff rings. Mt Warrnambool is a complicated hill, consisting of an outer, low tuff ring and an

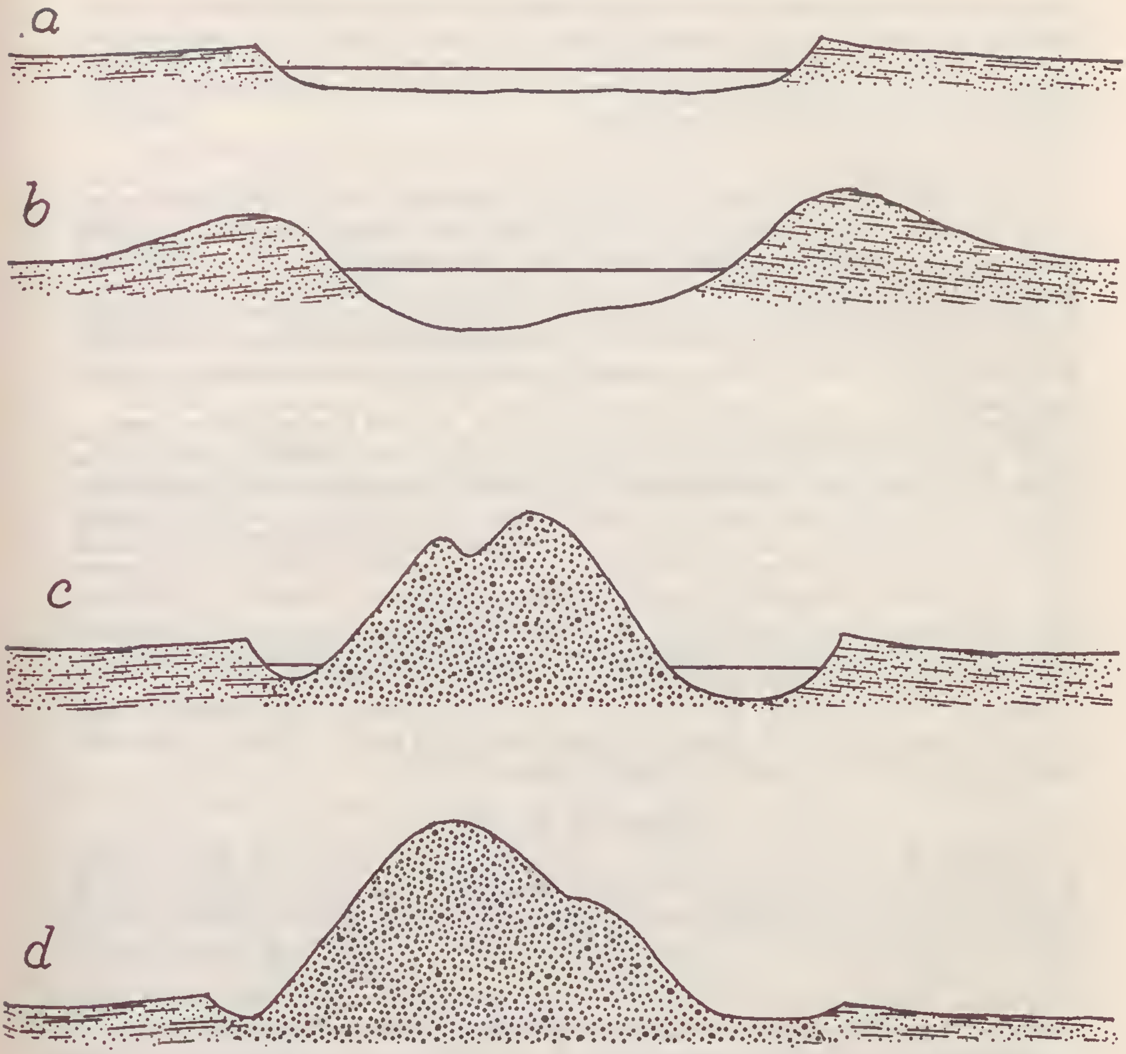

FIG. 1—Diagrammatic representation of the transition from a simple maar to a complex type. a is a simple maar, such as Keilambete, Elingamite or Purrumbete. b is a maar such as Bullenmerri or Gnotuk with higher hills around the edge and a deeper lake. c is a maar with a scoria cone growing in the centre of the lake, such as Tower Hill. d is similar to Tower Hill, but there is no lake and the scoria cone is the dominant feature, as at Mt Warrnambool, Ewans Hill, and Bostock.

inner high hill. The outer ring, which is highest on the E. and almost non-existent on the W. is similar to the outer rim of Tower Hill and to the maars, and has a diameter of about 2 miles. This could be a 'nested tuff ring' as definite evidence of collapse is missing, especially on the W. side.

Boutakoff (1963) has described Bridgewater Bay, Nelson Bay, and Grant Bay (all to the W. of Portland) as collapse calderas, each 2 miles or more in diameter,

and has shown the existence of a fault along the W. edge of Bridgewater Bay. Infilling with sediment and breaching by the sea has occurred, giving the present bays, the submarine topography of which reveals probable eruption points inside and around the submerged rim of the caldera. These calderas are Lower Pleistocene and older than the maars or Tower Hill.

Compex Volcanoes

Some hills do not fit directly into the classification given above because of complications during eruption. Several eruptions may occur in close proximity giving rise to a multiple volcano. In Victoria, the several hills of a multiple hill tend to be all of about the same size, as for instance at Mt Monmot, and it is not possible to distinguish main and parasitic cones. Generally the parts of a multiple volcano are similar in composition, as at the Wiridgil Hills which are all of scoria. When material of different sorts is present we have called the hills composite rather than multiple.

Mt Rouse is a composite hill of scoria and lava, with an elongate crater running E.-W. in the scoria part, and on the S. a smaller and more distinct crater with a basalt rim, which may be the remains of a fire-pit. The composite Mt Porndon has a large shield with a diameter of about 2 miles, in the centre of which are a number of scoria hills, partly arranged in concentric arcs. Staughtons Hill consists of a maar (Keayang swamp), a scoria hill (Mt Cunnies Hill), and a basalt-rimmed separate crater (L. Mumblin). Most composite hills appear to consist of individual hills which are genetically related, but it is possible that some, such as Staughtons Hill, are due to accidental superimposition of eruption points from different times, and not related genetically. Petrological work could be instructive here.

Mt Clay, Mt Eckersley, Mt Vandyke, and Mt Deception, of the Portland area, do not fit into any of the types of volcano described so far. They are smoothly rounded hills of bedded tuff, with basalt plugs and flows.

Features of the Vent

Craters are not always present, or they may be obscure, as at Mt Vandyke, Deception, Lawaluk, and Rebecca. Other volcanoes have perfect craters, such as Mt Leura, Noorat, and Elephant amongst the scoria cones, and Mt Hamilton among the lava cones. Mt Rouse, a complex volcano, has a large crater in the scoria part, with a perfect crater at a lower level in basalt. Craters can be several hundred feet deep as at Mt Noorat (500 ft) and Mt Leura (300 ft). The maars have craters often a mile or more across, but other craters are smaller, usually less than 400 yards.

Breached craters are common in scoria volcanoes, the breach taking the form of a gap in the crater rim, as at Mt Elephant. Many do not have a lava flow going through the breach and the breach, therefore, is not formed by lava break-through and outflow. At Mt Elephant, an accumulation of scoria debris lies below the breach, but in most cases there is no accumulation whatever. Some authors have indicated a preferred direction of breaching, usually maintaining that most breaches are on the W. side, correlating this with supposed wind direction at the time of eruption. Our observations (for the entire Newer Volcanic Province, not only the plains) indicate a random direction of breach, with, if anything, a maximum to the N. and NW.

Some breaches may occur by slumping of the wall into the crater, or down to the outside, due to explosive shock, settling, loss of liquid from the cone material in the form of squeeze-ups or the movement of lava through the cone walls from the

crater to the outside. The latter explanation may apply to Mt Elephant, where two flows appear to have emerged from the base of the cone. One flow may have caused part of the inside wall to slump down into the crater, while the other caused a section of the rim to slump down to the outside, thus lowering the rim and giving a breach.

Some hills appear to be breached at both ends, giving a dumb-bell shaped crater remnant as at Mt Eckersley. Mt Monmot consists of two adjacent craters, the W. crater breached to the W., and the E. one to the E. Mt Eccles has an elongate crater, with the lowest point to the N. end, but from this a very marked flow emerges.

Many craters are flat bottomed, due to a fill of debris and alluvium, e.g. Mt Hamilton, Wangoom, and L. Terang. Others, such as Noorat, have simple concave crater bottoms with very little fill and some, such as Mt Napier, have a convex boss in the middle of the crater. The E. Monmot crater has a small, steep-sided hump of congealed, scoriaceous lava, rather like a hornito.

A small spatter cone S. of Mt Eccles has an open vent. A small crater leads into a constriction about 15 ft wide, below which the shaft opens out like an inverted wine glass. The shaft goes to a depth of almost 100 ft, with a floor of large loose scoriaceous blocks, and walls festooned with lava stalactites. Withdrawal of magma after eruption is indicated, which is probably a common phenomenon but it has usually been destroyed by collapse.

Features of the Lava Flows

The lava flows that poured over the W. plains were not entirely uniform, and several types of flow occurred, associated with certain landforms.

Sheet Flows

These gave rise to the flattest of the lava plains and were formed by very liquid lava. Large areas were covered, but an examination of boring records shows that an average flow was only about 25 ft thick. Hanks (1955), in the region N. of Melbourne, and Condon (1951), in the Mt Cotteril area, were able to map distinct flows, and showed that even apparently flat sheets of lava were made up of many individual lobes. On the W. plains the original topography probably helped the rapid lateral spread of the lavas. Some bore records indicate several flows separated by layers of ejectamenta.

Consticted Flows

Some lava flows followed valleys and now still have the form of valleys, being thicker in depth but narrower laterally than the sheet flows. The youngest flows of this type, such as the Harman valley flow at Byaduk, still occupy their valleys and are not affected by subsequent erosion. Others have lateral streams, such as the Tyrendarra flow from Mt Eccles. In the Geelong area, Bowler (1961) has found several generations of constricted flows, the younger ones following the lateral streams that were formed alongside earlier flows.

The lava that flowed down the old valleys must have been very liquid for it flowed for many miles (at least 15 miles in the case of Byaduk, over 30 miles for the Mt Eccles flow), but some flows were more liquid than others. The very fluid ones reached their position of rest as liquids; in other cases the lava seems to have been congealing during flow and gives rise to 'layered lava' as exemplified at Byaduk. Here the lava is divided into many layers, separated by partings and lines of vesicles, and there is no vertical segregation on cooling. Skeats and James (1937) regarded

the layers as individual flows, but we believe they are formed by laminar flow within the basaltic lava.

Stony Rises

Much of the ground in certain volcanic regions is very irregular although tending to a plain on a broad scale. Hummocks and depressions, channels and ridges, make a completely confused topography with relief of usually only 20 ft or less called 'stony rises'. There appear to have been several varieties of this. Some were individual narrow flows of lava emerging from the base of a broad lava sheet. These are found especially on the S. shores of L. Corangamite. Differential draining of lava from beneath the skin of a partly congealed lava plateau caused elongated depressions if the surface sagged, and this type of stony rise is the most common. The drained channels can coalesce, so that the ridges break up into a number of isolated hillocks with accordant, often flat summits.

Other Features of the Flows

Where lava flows into water it solidifies into the peculiar form of pillow-lava, consisting of rounded masses of lava, each mass having a tachylitic chilled edge, and radial cracks in the more crystalline interior. There is a very fine example of pillow lava at Toolern Ck, Exford. This pillow-lava is unusual only in that it appears to have formed in fresh water rather than in the sea, and is associated with thin bands of alluvium.

Columnar jointing develops in stationary flows which cool fairly slowly. Crude jointing is present in most flows, but there are very good examples at Sydenham, and at Hopkins Falls on the Hopkins R.

Tumuli are small humps on a lava sheet, where localized pressure from underlying liquid forces up the early cooled lava skin into a bulge above the general level, without actually breaching it. Good examples are found near Mt Gellibrand. Tumuli associated with stony rises add to their complexity, and there is no clear dividing line between the two.

So-called lava blisters of Victoria have the form of very exaggerated tumuli, rising very steeply from their base, and cracked across their tops due to the great bending they suffer. The best examples are at Wallacedale, and have been described by Skeats and James (1937), who believed they were formed by gas pressure due to steam generated when a lava flow crossed a swamp. We have not been able to find any hollow blisters, and do not believe that this special explanation is necessary. The lava blisters are tumuli of exaggerated type, but still due to local lava pressure, and not to steam generated beneath the flow. The term 'lava blister' should be reserved for hollow features, such as exist in other parts of the world.

Boutakoff (1963) has found depressions 30-40 ft in diameter which he calls 'steam bubble' structures. These depressions are hemispherical or egg-shaped, surrounded by concentric joints, and occur in the Lower Pleistocene basalt along the coast to the W. of Portland. Boutakoff believes they are cavities left by steam and gas bubbles escaping from a viscous lava.

Where lava is drained from beneath an early formed skin, stony rises are not the inevitable result. If withdrawal takes place on a large scale, large broad depressions which are completely enclosed may be formed. Two such depressions are present near Exford (Meredith Sheet Grid Ref. 5243).

On the other hand, the lava skin may not collapse at all and, when lava is withdrawn, it merely leaves a space beneath, which is a lava cave, lava tunnel or

lava tube. Lava caves are known from Byaduk, Mt Eccles, Mt Hamilton, Mt Widderin, Mt Warrnambool, Parwan, Mt Porndon, and Mt Gisborne. Ollier and Brown (1963) have described these caves and discussed the mechanism of cave formation. The idea of Skeats and James (1937) that the caves consisted largely of great lava blisters which were buried under later flows is no longer acceptable. Descriptions of individual caves, together with surveyed plans and sections have been published in the *Victorian Naturalist* (Gill 1944, 1959; Ollier 1963) and others will be published in the same journal (Ollier in lit.).

Barriers and pressure ridges have been described by Skeats and James (1937). These are elongate ridges of basalt pushed up by movement of the underlying lava. Some are lateral to flows and late withdrawal of lava is partly responsible for their construction; others are transverse and formed in one operation. The Great Barrier of the Harman Valley flow is the best example; it is curved downstream, indicating differential flow between the centre and the sides of the lava stream.

Lineaments

In some volcanic areas, especially those with fissure eruptions, it is common to find volcanoes falling along a number of straight lines. It is hard to find such lines in Victoria. Mt Eccles is in line with at least 8 small hills or spatter cones, and a total of 20 or so vents, including that of L. Surprise which lies in an elongated crater. This is probably the most distinct evidence for lineaments in Victoria. Boutakoff thinks the lineament is related to the edge of an underlying laccolith structure, which has been indicated by gravity surveys.

From our own map no clear lineaments emerge. The Anakies are 3 scoria hills which appear to lie, *en echelon*, along a straight line, possibly related to jointing in the underlying granite. E. of Quarry Hill there are at least 5 small vents, not indicated on our map, which run in an E.-W. line parallel to the escarpment to the S. A number of N.-S. lines may be recognized in the maars of the Camperdown district —Gnotuk, Bullenmerri and Bostock; Ewans Hill, Cobrico, Elingamite; Terang, Staughtons Hill, Ecklin—but all these 'lines' contain very few points, and may be only imaginary.

Coulson (1954) attempted to construct a map of lineaments for the 123 points of eruption of the Daylesford district, although he was well aware of the difficulties of this. We have performed the experiment of giving a map of the points of eruption to 10 people; 10 sets of lineaments were produced, having little agreement with either Coulson's map or each other.

There is a noticeable concentration of volcanoes along the line Geelong-Camperdown-Heywood, which coincides with the axis of the Tertiary Basin (see Fig. 2).

Nature of the Volcanic Eruptions

It is commonly supposed that lava plains are erupted from fissures. This could be so in the W. District, but erosion has not yet revealed any such dykes. Certainly the Older Volcanics in E. Victoria were fed by many dykes, but most of the Newer Volcanic eruptions appear to be of central eruption type. The lava plains, when mapped by Hanks (1955) and by Condon (1951), have been shown to consist of individual lobes which can be traced to distinct points of eruption. Mt Rouse, Mt Porndon, Mt Napier, and Warrion Hill, are all surrounded by expanses of flows and stony rises which almost certainly are derived from these points of eruption, and there are many other examples. The form of the cones suggests central type eruption, and the lack of lineaments is regarded as evidence against fissure eruptions.

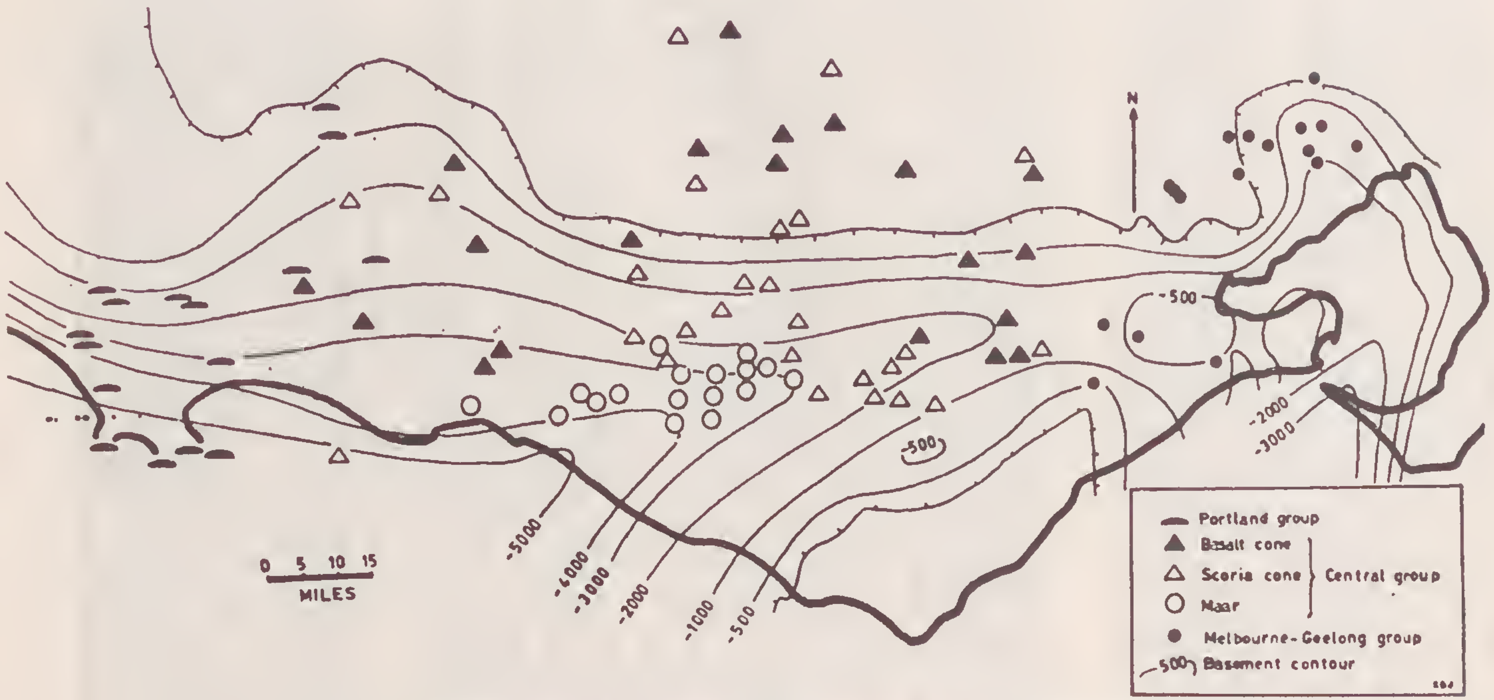

FIG. 2—The distribution of volcanoes on the W. plains in relation to the Tertiary basin. The classification shown is only approximate.

It must be borne in mind that the cones represent only the last period of activity, and the earliest type of eruption may have been different, but the balance of evidence indicates that we have a region of central eruption activity.

The scoria cones are probably monogenetic—i.e. the result of one continuous series of eruptions rather than the numerous eruptions, widely separated in time, from the one site which are typical of pyroclastic volcanoes. Rittmann (1962) suggests that, while pyroclastic volcanoes are usually formed by eruption of viscous magmas (which probably does not apply to Victorian volcanoes), small pyroclastic volcanoes can be formed from fluid magmas, provided the pressure behind the magma is too weak for a lava stream to follow the first explosive outbreak. Such structures are often formed during the last phase of a mixed eruption and overlie previous lava streams. This would appear to be common in the W. plains of Victoria.

As a very broad generalization, the sequence of eruption on the plains appears to have been an outpouring of lava to give a lava plain, stony rises and flows, followed by formation of scoria cones. Some lava flows may be erupted along with the ash and scoria, as at Mt Rouse. At Mt Porndon, a distinct disc of lava was erupted on top of earlier lavas before the formation of several scoria cones. Lawaluk may have formed as a small scale disc of the Mt Porndon type, not followed by any pyroclastics. There are also many simple basalt hills with no scoria, such as Mt Hamilton and Mt Cotteril.

According to Rittmann, pumice cones are encountered more frequently than scoria cones, but presumably he is thinking of acid igneous activity. In Victorian Newer Volcanics, the fluid, basic lavas have given rise to many scoria cones, and only a few volcanoes of the maar type with fine pyroclastics. The maars may seem fairly common on the plains, but for the province as a whole they are rare.

Some of the maars, such as Wangoom, Elingamite, and Cobrico, may represent single explosive eruptions neither preceded nor followed by extrusion of lavas. Mt Warrnambool, Mt Leura, and Bostock Hill are maars with later multiple scoria cones built on the same centre of eruption.

It is generally supposed that maars are formed by violent explosions, perhaps where hot lava meets ground water. The maars of the W. plains all occur in positions where this is feasible, as they are usually underlain by limestone. Thin bedding in the pyroclastics of the maars indicates that the eruption was not cataclysmic, and this is a feature of maars in other regions, such as the Eiffel maars.

Rittmann has invented an explosion index (E) which is the percentage of fragmentary material in the total volcanic material produced. We have attempted to calculate the explosion index for the Newer Volcanics of Victoria; this can only be done roughly, but working within reasonable though wide limits we found E to be about 1%. This seems surprisingly low, but shows that the lava flows, though thin, are extensive, while the more noticeable scoria cones are really much smaller in total volume.

This may be compared with the following figures from Rittmann (1962):

Area	E (%)
Island arcs	95
Southern Italy	41
African Rift Valleys	40
Iceland	39
Atlantic and Indian Oceans	16
Pacific	3

Even allowing for a large error in our calculations it is clear that the explosion index for the Newer Volcanics is very low. According to its E, the volcanic activity should correspond with the Hawaiian or Icelandic type of eruption. However, the Victorian eruptions are not of Hawaiian type (lava shield) and if we are correct in believing fissure-eruptions are not dominant, then the eruptions cannot be of Icelandic type (distinguished by its fissure eruptions). The individual scoria cones in Victoria are probably formed by explosive eruption of Vulcanian or Strombolian type, but of a more basic lava than usual.

Thus, the Newer Basalts may represent a distinct type of geomorphic/petrographic province, characterized by extensive plains of basaltic lava, and many small, monogenetic, central eruption hills, formed in the last stages of vulcanicity.

Weathering, Soils, and Erosion

In the youngest volcanoes even small-scale features are preserved intact. Near Mt Eccles, the small spatter cones have perfectly preserved ropy lava and lava stalactites, even in exposed positions. A rough assessment of ages can be based on the preservation of cones or flows—the Harman valley flow from Mt Napier, for instance, shows an aa surface, still almost complete, whereas old flows, such as from nearby Mt Pierrepoint, are scarcely distinguishable.

The youngest flows are remarkably fresh, with virtually no soil cover, as in the N. flow from Mt Eccles. Stony rises, wherever they occur, are little altered or eroded, so are believed to be fairly young features, and the volcanoes from which they were erupted are therefore fairly young also as, for instance, Mt Rouse, Mt Porndon, Mt Eccles, and Warrion Hill.

The older flows of the Hamilton and Cressy districts show much spheroidal weathering, with the development of deep soils including laterites. Except where covered by sediments, basalts of the Portland area are deeply lateritized (Boutakoff 1963), as is also Mt Clay.

Weathering and soil formation can often only be used as a rough guide in dating since many factors are in action besides the time factor. Krasnozems, Red-brown Earths and Black Earths may all be found on the basalt from one volcano. Often complicated soil profiles are present, and the significance of many observed soil relationships is not known. Gibbons and Gill (1964), however, have attempted the recognition and classification of 'soil landscapes' which, to a large extent, indicate the relative ages of different flows.

The scoria cones have little run-off due to their porosity and they naturally show little erosion although, in fact, even the lava cones show surprisingly little erosion. In some of the older volcanoes, erosion has given rise to a general rounding rather than gulleying and the original forms are obscure. Mt Pierrepoint and Mt Bainbridge, e.g. are low and rounded with ill-defined breached craters. Volcanoes of the Portland area (Mt Clay, Richmond, Vandyke, etc.), including both lava volcanoes and tuff cones, are rounded hills with little indication of original shape. The sequence of erosion described by Kear (1957)—(1) volcano stage, (2) planeze stage, (3) residual mountain stage, (4) skeleton stage—cannot be applied in Victoria.

Volcanoes of the Ballarat area show some gulleying, but within the area of the plains, gulleys are rare. Mt Eckersley has a gulley running from the crater on its E. flank. Mt Vandyke has ravines on the E. slopes which have exposed the underlying tuff (Boutakoff 1963).

Mt Noorat is distinguished by a number of radial gullies which divide its flanks into planeze-like sectors. However, there is some evidence that these gullies are not

normal erosion gullies; they do not breach the crater at their head, and they end in blind, enclosed depressions at the base. Possibly the gullies are grooves formed by lahars or landslides soon after eruption ceased.

The blocking of drainage by lava flows naturally causes modifications to the river systems, and a number of the drainage diversion systems have been studied. The most common modification is to have a lateral stream at the edge of a lava flow, or sometimes twin laterals, one on each side. Some of the very young flows, such as the Harman valley flow, have not developed any lateral streams at all. Others, such as the Tyrendarra flow from Mt Eccles, have well developed lateral streams, even though young. The actual incision of lateral streams will depend on the size of the catchment, amount of run-off, and other factors besides age. Some of the lateral streams near the edge of the highlands have incised valleys several hundred feet deep. In the Geelong area, lateral streams of one period gave rise to valleys that were then filled by later flows (Bowler 1961). Similar complexity has been discovered in the Bacchus Marsh area (Fenner 1925).

Dating of Volcanoes

A complete discussion of the attempts which have been made to date the vulcanicity of Victoria is beyond the scope of this basically physiographic paper but, since an understanding of the physiography does depend on the age and chronology of the volcanics, a brief review of the methods of dating which have been applied in Victoria is necessary here.

Weathering, soil formation, and erosion are clearly good indicators of relative age, but they have to be used with some caution because, as explained in the section above, there are more factors in operation than age. For the grosser deductions, however, such features as preservation of detail or lack of it, depth of soil, and drainage modifications provide useful clues in establishing a relative chronology. Flows may be dated relatively by their superposition, as in Hanks (1955), and the flows can then be traced back to their volcanoes to give an age sequence for the volcanoes themselves. Relative dating of flows by studying drainage diversion is also possible, as mentioned above.

In the SW. area and around Geelong, a number of volcanoes can be dated relative to extensive sheets of aeolianite which make a convenient reference age. Mt Duneed, in the Geelong district (Coulson 1938), and Cape Nelson and Bald Hill (Macarthur) are all pre-aeolianite, while Mt Eccles and Mt Napier are post-aeolianite.

Cape Grant and Cape Nelson have been dated by reference to a 100 ft marine platform, which truncates tuffs and plugs, and is believed to be of Middle Pleistocene age. Mt Eccles has been dated relative to a 15 to 20 ft beach which rests on part of the flow.

If we can date the material underneath a volcano we can get its maximum age. Too often in the past there has been a tendency to assume the underlying deposits give an actual age for the volcanics, and flows have been dated as Lower Pliocene or earlier on insufficient evidence, when there is possibly an unconformity between the underlying material and the volcanics. This distinction is of less importance when the underlying material is of recent age, for other dating methods become available. In a number of places artefacts have been found beneath volcanic material (Gill 1953). At Mt Gambier in South Australia, implements and hearths have been found beneath the volcanics and artefact dating and radio-carbon dating are pos-

sible. The younger volcanoes are certainly within the range of carbon 14 dating and results are awaited eagerly.

A few fossils have been recovered from within volcanic deposits, but not in sufficient numbers to be of much use in dating. Fossils found in lava caves give a minimum age of their flow, for the volcano and caves may have been in existence a long time before they were occupied. Wakefield (1964) has described this line of enquiry in detail.

Many craters and maars have swampy deposits in their bottoms, and there are many swamp deposits around the margins of flows due to drainage modifications. This suggests that pollen analysis might eventually be used for relative dating of the volcanics. Preliminary tests have been made and it has been found that, although only a little pollen is present in crater samples, the method appears to be feasible. It will, however, take a considerable time to build up a pollen sequence.

Palaeoclimatology is a rather indirect way of dating but has been used a little. Buckshot gravel, laterite formation, and soil types have been taken as indicators of former climates and tentatively correlated with certain times in a Pleistocene chronology. The asymmetric distribution of ash around Wangoom and Mt Warrnambool indicates a W. wind, from which Gill (1950) deduces that the eruption took place during the last period of glaciation when W. winds would be more prevalent over Victoria.

The Sequence of Vulcanicity in Victoria

From the previous section it is apparent that, although there are many possible means of dating Victorian volcanoes and volcanic activity, actual progress so far has been small, and we are just moving into a period when rapid advances in the establishment of chronology can be expected. However, a few generalizations can be made at present.

It has been suggested that there is a tendency for the vulcanicity in Victoria to move to the W. with time, so that the older volcanoes are in the E., the youngest in the W. This neat generalization does not seem to have much basis in fact.

The Portland group, in the far W. of Victoria, consisting of Eckersley, Sugarloaf, Cape Bridgewater, Cape Nelson, Cape Grant, Vandyke, Deception, Richmond, Kincaid, Bald Hill, and Clay are old volcanoes—pre-aeolianite, Lower Pleistocene (according to Boutakoff), well rounded and weathered. Farther N. are Mt Pierrepoint and Mt Bainbridge, old weathered remnants, possibly comparable in age with the Portland group.

In the N. central part of the plains, weathered basalt cones of the type of Mt Widderin occur. In the E. limits of the plains, the Melbourne-Geelong group also consists of weathered basalt cones. These two groups may be similar in age, and we consider both are younger than the Portland group.

The central part of the plains contains many fresh scoria cones, such as Mt Elephant and Mt Noorat. The S. central area contains the maars. These two groups are younger again than the basalt cones mentioned above, and the maars are probably younger than the scoria cones.

Scattered among the volcanoes mentioned are the very young volcanoes which erupted at the close of the volcanic period. Mt Hamilton is younger than the volcanoes surrounding it, while the scoria cones of Mt Rouse and Mt Napier are both youthful. Mt Eccles in Victoria, and Mt Gambier and Mt Schank in South Australia, are the youngest in the plains.

Comparison with the volcanoes of the uplands is difficult, but most of the vul-

canicity in the Ballarat and Daylesford regions is perhaps of the middle period—younger than the Eckersley group, but certainly older than the Gambier-Eccles period.

Far from moving to the W., the eruptions in the plains have moved progressively S., to finally concentrate over the axis of the Tertiary basin (see Fig. 2). Detailed mapping of physiography and surficial geology should make this picture much clearer, and it should not be very long before a fairly detailed chronology can be applied to the W. plains.

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FIG. 3—Key to the volcanoes of the W. plains.

TABLE 1

1	Vandyke	33	The Sisters	64	Wallinduc
2	Mt Deception	34	L. Keilambete	65	Vaughans Is.
3	Little Kincaid	35	Terang	66	The Basins
4	Mt Kincaid	36	L. Terang	67	Warrion Hill
5	Mt Richmond	37	Staughtons Hill	68	Alvie
6	Cape Bridgewater	38	Ecklin	69	Red Rock
7	Sugarloaf	39	Noorat	70	Robertsons Hill
8	Mt Eckersley	40	The Bald Hill (Tatyoon)	71	Quarry Hill
9	Mt Clay	41	Weejort	72	Mt Rebecca
10	Cape Nelson	42	Mt Hamilton	73	Mt Hesse
11	Cape Grant	43	The Peak	74	Mt Gellibrand
12	Lawrence Rocks	44	Meningorot	75	Mt Mercer
13	Bald Hill (Macarthur)	45	Ewans Hill	76	Lawaluk
14	Mt Eccles	46	Cobrico	77	Gow's Hill
15	Lady Julia Percy	47	Elingamite	78	Mt Pleasant
16	Mt Bainbridge	48	Mt Koang	79	The Cap
17	Mt Pierrepoint	49	Gnotuk	80	Mt Pollock
18	Mt Napier	50	Bullenmerri	81	Wurdi Buloc
19	Ripponhurst	51	Bostock	82	Mt Moriac
20	Vine Bank	52	Banangil	83	Mt Duneed
21	Blackwood	53	Vite Vite	84	Anakie
22	Mt Rouse	54	Mt Elephant	85	Bald Hill (Bacchus Marsh)
23	Green Hills (Penshurst)	55	Mt Kurweeton	86	One Tree Hill
24	Green Hills (Winslow)	56	Mt Leura	87	Spring Hill
25	Mt Taurus	57	Monmot	88	Green Hill
26	Tower Hill	58	Mt Widderin	89	Mt Cotteril
27	Wangoom	59	Little Elephant	90	Greek Hill
28	L. Munderong	60	Mt Myrtoon	91	Black Hill
29	Tank Hill	61	Wiridgil	92	Kororoit
30	Mt Warrnambool	62	Purrumbete	93	Atkinson
31	Mondilibi	63	Mt Porndon	94	Diarmuids Hill
32	Mt Shadwell				

Explanation of Plates

(Aerial photographs reproduced by permission of Lands and Survey Department.)

PLATE LII

Lava cone. An aerial view of Mt Hamilton with stereo cover, and a ground view of the crater, looking N.

PLATE LIII

Scoria cone. An aerial view of Mt Elephant with partial stereo cover, and a ground view from the NE.

PLATE LIV

Maar. An aerial view of L. Elingamite, and a ground view of Keilambete, looking E.

PLATE LV

Complex volcano. An aerial view of Mt Rouse with partial stereo cover, and a ground view of the lava crater with the scoria mound in the background.

TABLE 2

NAME	NO.	ALTITUDE (Ft)	HEIGHT (Ft)	SYNONYM	REMARKS
ALVIE	68	750	250		Multiple scoria cone. Several closed depressions.
ANAKIE	84	1310	500	The Anakies, Anaki, Anaki Youwan	3 elongate scoria mounds, and a small tuff ring or crater to N.
ATKINSON	93	459	50		Low basalt cone.
MT BAINBRIDGE	16	800	100		Basalt dome, very weathered. Craterform.
BALD HILL (Macarthur)	13	600	200		Rounded hill of tuff and ejectamenta.
BALD HILL (S. of Bacchus Marsh)	85	731	200		Basalt and scoria hill.
THE BALD HILL (Tatyoon)	40	1117	150		Scoria hill, highest to W., with perfect crater 400 yds across and 50′ deep.
BANANGIL	52		100		Low basalt dome.
THE BASINS	66	500	50		Double scoria cone with crater lakes.
BLACK HILL	91	190	100	Cowie's Hill	Scoria cone.
BLACKWOOD	21		50		Basalt hill, steep to E. and gentle slope to W., with squeeze-ups.
BOSTOCK	51	800	200	Waller's Hill	An outer maar with a multiple scoria cone inside.
CAPE BRIDGEWATER	6	450	450	Stony Hill	Eroded remnant of volcanic complex or caldera. Tuff and basalt.
BULLENMERRI	50	900	300		Lake 263′ deep. Possibly 3 coalescing maars.
THE CAP	79	425	50		Scoria cone.
MT CLAY	9	622	500		Broad flat-topped hill, consisting largely of tuff, with some lava flows.
COBRICO	46	450	50		Maar. Flat bottom largely swampy. Open to SW.
MT COTTERIL	89	669	100	Cottril	Simple lava cone.
MT DECEPTION	2	524	200		Well rounded hill consisting largely of tuff.
DIARMUIDS HILL	94	196	50		Lava cone.
MT DUNEED	83	340	100		Low basalt hill.
MT ECCLES	14	584	200	Eels	A complex of several aligned scoria and spatter cones, an elongate crater (L. Surprise) and flows. Lava caves.
MT ECKERSLEY	8	537	400	Bell's Hill	Low angle tuff conc. Elongate crater.
ECKLIN	38	500	100		Maar, outlet to NW. Swamp filled.
MT ELEPHANT	54	1294	780	Clarke	Steep-sided scoria cone. Breach to NE. Stony rises around.
ELINGAMITE	47	500	50		Maar. Lake filled. Cliff to E. side. Thin bedded tuff.
EWANS HILL	45	893	500	Gnarogein, Emu, Mt Ewen	Double scoria cone, with partial maar rim on E. side.
MT GELLIBRAND	74	56	350		Irregular cone breached to S. Mostly basalt.
GNOTUK	49	600	100		*Maar. Lake 103′ deep.*

TABLE 2—*continued*

GOW'S HILL	77	577	75	Green Hill	Low basalt hill.
CAPE GRANT	11	200	200	Cape Sir William Grant	Eroded remnant of volcanic complex or caldera. Basalt and tuff.
GREEK HILL	90	293	75		Remnant of basalt cone.
GREEN HILL	88	476	100	Mt Mary	Scoria cone with breached crater.
GREEN HILLS (Winslow)	24	400	100		Crater with low, irregular wall.
GREEN HILLS (Penshurst)	23	701	100		Irregular hill with many humps and depressions, composed of vesicular basalt and agglomerate. Some basalt squeeze-ups.
MT HAMILTON	42	1035	250		Low basalt cone. Perfect crater. Lava caves.
MT HESSE	73	542	200		Lava cone. Crater, breached to E.
L. KEILAMBETE	34	450	30		Maar.
MT KINCAID	4	664	200		Rounded hill, mostly basalt.
MT KOANG	48	894	300	Together with Kurweeton makes Cloven Hills	Scoria hill, breached crater open to W.
KOROROIT	92	782	200	Mt Misery	Basalt hill showing successive points of eruption.
MT KURWEETON	55	890	400	Kurtweeton. Cloven Hills with Mt Koang	Scoria cone with a few basalt flows.
LADY JULIA PERCY	15	152	152		An island, much eroded, originally with a centre of eruption (tuff cone).
LAWALUK	76	1213	100		Flat topped disc of basalt. 200 yds across.
LAWRENCE ROCKS	12	almost submerged			Possibly remnants of Cape Grant caldera.
MT LEURA	56	1027	500		Outer maar with nested scoria cones. Crater 300′ deep.
LITTLE ELEPHANT	59	611	100		Simple scoria cone.
LITTLE KINCAID	3	560	50	Piccaninny Mt	Basalt cone, largely obscured.
MENINGOROT	44	759	250	Meningoort Miningorat Meningoret	Elongate scoria cone with several subsidiary craters.
MT MERCER	75	1404	200		Scoria cone with well defined crater ½ mile across breached to N.
MONDILIBI	31		50		Steep-sided, elongate basalt hill with no crater, and many squeeze-ups.
MONMOT	57		200		Twin scoria cones, breached in opposite directions.
MT MORIAC	82	834	350		Rounded basalt hill.
L. MUNDERONG	28	400	50		Crater or maar, ½ mile across, with swamp and some open water. Open to N.
MT MYRTOON	60	701	200		Scoria cone with some basalt. Well defined crater.
MT NAPIER	18	1453	500		Multiple scoria cone, with some basalt, especially in lower parts.
CAPE NELSON	10	300	300		Eroded remnant of volcanic complex or caldera.
NOORAT	39	1026	500	Nooat	Scoria cone with large, perfect crater 500′ deep. Some basalt tongues, and radial gullies.
ONE TREE HILL	86	505	100		Lava cone.

TABLE 2—*continued*

THE PEAK	43	957	50	Mt Fyans	Low scoria hill amongst stony rises.
MT PIERREPOINT	17	936	100		Rounded basalt hill, with a crater breached to N.
MT PLEASANT	78	550	150		Elongate lava cone.
MT POLLOCK	80	609	200		Basalt cone, much eroded.
MT PORNDON	63	949	350		Multiple scoria cone, overlying a disc-like lava flow with caves. Stony rises around.
PURRUMBETE	62	600	100		Maar, highest to E. Lake 150′ deep.
QUARRY HILL	71	622	100		Composite hill with basalt over scoria.
MT REBECCA	72	523	70		Low basalt hill, featureless except for a lava squeeze-up near summit.
RED ROCK	69	700	300	Red Hill	Multiple scoria cone with some bedded tuff. Several craters occupied by lakes.
MT RICHMOND	5	710	250		Composite hill, largely obscured by sand.
RIPPONHURST	19	700	100		Low basalt hill, well weathered.
ROBERTSONS HILL	70	715	250	Kerang-e-Moorah	Basalt hill.
MT ROUSE	22	1213	300		Composite hill, main part scoria cone. Well defined basalt crater to S.
MT SHADWELL	32	965	450		Multiple scoria cone.
THE SISTERS	33	600	150	Sister Rises	Multiple tuff cone, with small amounts of basalt.
SPRING HILL	87	700	150		Lava dome with large crater.
STAUGHTONS HILL	37	600	200	Mt Cunnies Hill (E. Peak) & Keayang Swamp (maar)	Complex hill with a maar, and also a smaller crater in basalt.
SUGARLOAF	7	468	250		Composite hill. Crater facing S.
TANK HILL	29	400	100		Possible maar, with outcrops of bedded tuff on low, E. side, and larger hill to W. of flat-bottomed crater.
MT TAURUS	25	396	150		Irregular low basalt hills, with possible crater open to E.
TERANG	35	579	150		A scoria cone with a few thin basalt flows. Crater breached to SE.
L. TERANG	36	500	50		A maar. Now dry. Mostly tuff, but some agglomerate and basalt.
TOWER HILL	26	323	250		Nested caldera or maar.
VANDYKE	1	606	300	Good Hill	Elongate tuff cone, largely obscured.
VAUGHANS ISLAND	65	400	50		Scoria cone, now an island in L. Corangamite.
VINE BANK	20	400	100		Low basalt hill of reddish vesicular lava.
VITE VITE	53	942	100		Low basalt cone. Stony rises.
WALLINDUC	64	850	100		Asymmetric basalt hill.
WANGOOM	27	243	100	L. Wangoom	Maar, with mostly country rock. Also ash and basalt.
WARRION HILL	67	922	400	abo. Labaam	Basalt plateau. No crater. Stony rises to N.
MT WARRNAMBOOL	30	712	400		Composite scoria hill, nested within maar.
WEEJORT	41	1211	150		Irregular multiple hill. Basalt, and possibly scoria.
MT WIDDERIN	58	1132	200		Low basalt cone. Stony rises around, especially to SW. Lava caves.
WIRIDGIL	61	700	250	Wiridgil Hills Woridgil	Multiple scoria cone. Many humps and depressions. Bedded ash and scoria, with bombs. Faults and contorted ash.
WURDI BULOC	81	550	50		Basalt hill.